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Transdisciplinary Collaborative Research Exploration for Undergraduate Engineering Students*

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This paper describes the creation of a Transdisciplinary Design Studio (TD^{2}S) for Collaborative Research and Education (CORE) in the Department of Mechanical Engineering at Texas Tech University and a study of this pedagogy for undergraduate engineering students. More specifically, this paper highlights a project-based TD design class which encouraged small student research groups to take on new behaviors of work—collaboration and teamwork—to solve complex problems. To create engagement in the class, an active learning and design-based research pedagogy was incorporated. Three main components (digital learning, creativity tools & techniques, and domain experts) of the TD design studio were examined for their contribution to student learning. We highlight the overlooked role of transdisciplinary design training in the undergraduate research experience and make specific reference to the impact of these pedagogical techniques on the learning outcomes for both Caucasian and under-represented minorities. Students' collaboration and creativity skills (TD skills) were tested and the results are presented. The ultimate goal of the TD class is to promote the creative, innovative, and divergent thinking of students.

This research study validated that TD-methods support the learning of underrepresented groups: transdisciplinary practice showed positive impact on underrepresented minority students' learning.

Keywords: transdisciplinarity; engineering education; transdisciplinary design studio; collaborative research; collective intelligence

1. Introduction

The purpose of this paper is present the findings of a study designed to test transdisciplinary (TD) approaches to undergraduate engineering education in an effort to improve STEM learning outcomes and generate new knowledge about effective practices in undergraduate education. In this paper, we discuss the outcomes of testing the use of TD pedagogical techniques. These are techniques used to create more engagement and collaboration in the classroom. This paper also makes brief reference to the teaching of TD research methods, which happened in the following semester. However, the bulk of the paper addresses the experiment and outcomes for course 1, which only focused on TD skills such as collaboration, creativity, and using outside knowledge to better understand complex problems. Recent studies suggest engineering education must evolve to teach a more holistic approach to problem solving to prepare students for the growing complexity of problems inherent in today's society. This project is a quasi-experimental study of the impact of transdisciplinary (TD) project-based learning in STEM education using a digital learning platform and a diverse cohort of undergraduate students.

Definitions of TD research go back to the early 1970s [1, 2]. "Transdisciplinarity can be defined as the practice of acquiring new knowledge through education, research, design, and production with a broad emphasis on complex problem solving and the use of knowledge and techniques from multiple scholarly disciplines. TD methods are unique in their ability to bring discipline-specific knowledge together holistically in order to clove complex problems. The goal of transdisciplinary practice is to improve students' understanding of complex issues by extracting the valuable aspects of typical academic disciplines and thereby generating both a more integrative and universal solution to support an issue of importance to society." [3–6].

An interdisciplinary (ID) methodology has been defined as "two or more disciplines which combine their expertise to jointly address an area of common concern" [7, 8]. "Interdisciplinary approaches integrate separate disciplinary data, methods, tools, concepts, and theories in order to create a holistic view or common understanding of complex issues whereas transdisciplinary approaches are comprehensive frameworks that transcend the narrow scope of disciplinary world views through an overarching synthesis [9]". Transdisciplinary (TD) research includes cooperation within the scientific community and a debate between research and society at large. TD research therefore transgresses boundaries among scientific disciplines and between science and other fields and includes deliberation about facts, practices and values [10].

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> "Convergence: facilitating transdisciplinary integration of life sciences, physical sciences, engineering, and beyond is an approach to problem solving that cuts across disciplinary boundaries. It integrates knowledge, tools, and ways of thinking from life and health sciences, physical, mathematical, and computational sciences, engineering disciplines, and beyond to form a comprehensive synthetic framework for tackling scientific and societal challenges that exist at the interfaces of multiple fields. By merging these diverse areas of expertise in a network of partnerships, convergence stimulates innovation from basic science discovery to translational application. It provides fertile ground for new collaborations that engage stakeholders and partners not only from academia, but also from national laboratories, industry, clinical settings, and funding bodies" (National Research Council of the National Academies, [11]).

The expected results of TD research and education are: emphasis on teamwork; bringing together non-academic experts and academic researchers from diverse disciplines; developing and sharing of concepts, methodologies, processes, and tools; all to create fresh, stimulating ideas that expand the boundaries of possibilities, and more effectively target real-world problems. The TD approach teaches students to seek collaboration outside the bounds of their professional experience to make new discoveries, explore different perspectives, express and exchange ideas, and gain new insights.

There has been a recent more powerful focus in engineering education on preparing students to solve real-world, complex problems. Dima and Zabinski focus on the need to teach Industrial Engineering students about incorporating a sensitivity and knowledge around sustainability into their design process [12]. Ozaltin et al., show the need to teach even undergraduate students to work collaboratively to generate the innovation that is needed to solve complex problems [13]. Mena at al., argue for the need to initiate all students, including undergraduate students, into the process of doing real-world engineering work, and not just focusing on rote memorization of concepts or equations [14]. Mehta et al., argue for the need for engineering education to include social and humanitarian components so that students are primed to think about how engineering design affects real people in multivarious contexts [15]. All of the scholars highlighted above show the need for engineering education to focus on complex problems, and the need for more collaborative, critical, and nuanced thinking about design issues and social impact.

TD research and education also focus on leveraging intellectual diversity, collaborative effort, cross-pollinating knowledge, and critical thinking to address real-world problems. The tools of TD—the mindset, the content knowledge, the social-impact-based design process—are all geared toward providing students with the preparation they need to see complexity, and to address those complex problems in innovative ways.

2. Overview of the transdisciplinary senior design course

In fall of 2015, the Mechanical Engineering Department at Texas Tech University initiated a two semester transdisciplinary senior design course sequence emphasizing collaborative, cross–disciplinary team based research efforts to engage and motivate students through hands-on transdisciplinary learning experiences. This is a one year course. The first semester focused more on teaching collaborative and innovative engagement and brainstorming practices. While there was some work done to talk about how to do research using TD methods, more of our time was focused on how to create a highly collaborative and innovative space to come up with ideas.

Four foundational core modules were covered to prepare students for a variety of subjects to support complex problem solving. The TD core modules developed for the advanced programs were modified for the undergraduate-level by the leading author of this paper. The content of the TD core modules, based on engineering design principles, included information and knowledge common to multiple disciplines and provided the students with a foundation in the TD skills required to identify, frame, and address important practical problems that cut across disciplinary boundaries. Four core modules were:

1. Complexity Management & Decision Making.
2. Transdisciplinary Design Process & Sustainable Development.
3. Transdisciplinary Discovery and Innovation.
4. Transdisciplinary System and Product Development.

2.1 *Transdisciplinary Design Studio (TD^2S)*

The Transdisciplinary Design Studio (TD^2S) for Collaborative Research and Education (CORE) was integrated with the new TD course. As shown in Fig. 1, the Transdisciplinary Design Studio is composed of three elements: technology embedded learning, creativity tools & techniques, and domain experts.

Technology Embedded Learning (TEL) has been engaged in classrooms and continues to grow. Social media and video platforms have connected our classrooms with others across the world to broaden our horizons—to explore a new field of knowledge, to become cognizant of possibilities outside of one's respective discipline. In this new

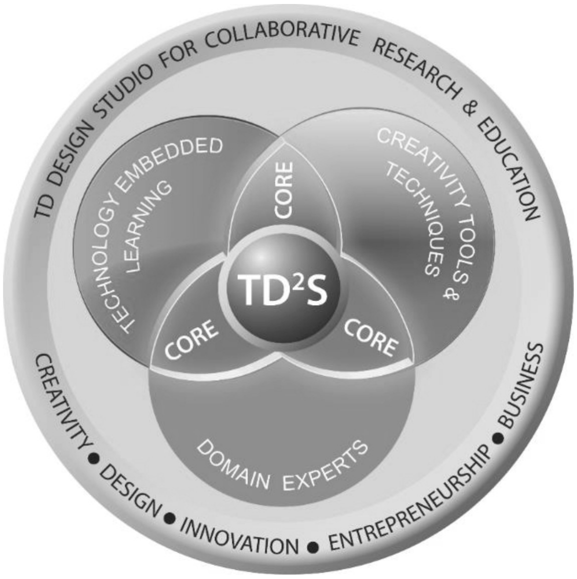

Fig. 1. TD Design Studio (TD^2S) for Collaborative Research & Education (CORE).

TD design course, we have focused on the use of the following educational technology to provide our students with the prospect to create, collaborate, communicate, and to enhance learning and knowledge sharing for problem solving.

- Email
- Video-Audio conferences (Ex. Blackboard Collaboration Tools)
- In-class video recordings
- Discussion boards (Ex. Blackboard forums)
- Face to face recorded meetings (Recorded by students in Video or Blackboard Collaborate format)
- Tablet and laptop
- Smart phone
- File sharing software and document editing (Ex, OneDrive, Dropbox)

Students' interactions, communications and discussions were recorded and saved on cloud and hard drive by using Texas Tech University's Microsoft Office 365 Tools and Blackboard Collaborate tools. Emails were tracked by asking students to carbon copy their email to teaching assistants. Student interactions in Blackboard Collaborate were recorded automatically and stored in the Blackboard cloud storage. Additionally, the video and audio files were downloaded and captured from time to time by using screen capturing software and they were stored in OneDrive and hard drive for back-up purposes. All class meetings have been recorded by using a camera recorder and video files were converted to user friendly video formats and stored in local hard drive and cloud storage environment.

Technology embedded learning platforms provided students the ability to:

- interact with "research groups" through interactive discussions,
- interact with the teacher/expert through an integrated video conference along with a shared, interactive whiteboard,
- form teams with other learners, share files, engage in active discussions, and conduct a group online video conference with a shared, interactive whiteboard,
- form "chat" connections with team members and saving the chat discussions.

Domain Experts: with TEL platform, student groups also were able to contact domain experts, including non-academic researchers.

Creativity Tools & Techniques

In this TD class, students learned skills and techniques needed to be highly creative when they take a job after graduation. Through the use of TD methods, students can learn: how to become more creative, discover a range of innovation techniques for producing creative ideas; how to decompose complex problems to understand how various parameters relevant to the problem are interrelated; how to collaborate and share ideas on achieving collective results; how to hold each other accountable for delivery according to their plans; how to openly discuss conflicting ideas; how to embrace critical dialogue and debate; and how to trust each other.

The following creativity and collaboration work tools were used as part of this course: Interpretive Structural Modeling (ISM), Design Structure Matrix (DSM), Axiomatic Design (AD), Structural Equation Modeling (SEM), Social Cognitive Career Theory (SCCT), Objectives Tree Method, Kano Model Analysis, Critical to Quality Characteristics (CTQ), KJ Method, Total Quality Management (TQM), Six Sigma, Quality Function Deployment (QFD), House-of-Quality, Theory of Inventive Problem Solving (TRIZ), Robust Design (RD), Statistical Decision Making, Taguchi Methods, and Design of Experiments.

2.2 Changing classroom culture

In this TD design class the following three important classroom culture changes were implemented. Our goal was to establish and maintain a learning environment that supports and motivates students to do their personal best. Thus, we aimed to:

1. Create a relaxed environment—enhance and create an inviting classroom,
2. Use student-centered learning techniques—

shift the aim of instruction from the teacher to the student,
3. Give students freedom—the will to be responsible for their performance.

3. Implementing transdisciplinary design/ research process

To obtain the desired research outcome for a system design, the proposed 5-step, TD research process model was used (see Fig. 2):

1. Identifying social issues;
2. Building a collaborative research team and collective understanding of the problem;
3. Developing collective intelligence and producing transferable new STEM knowledge through collaborative research to solve the societal problem in question;
4. Problem decomposition;
5. Knowledge creation and integration.

As shown in Fig. 2, TD design/research process starts by identifying social issues – complex problem. Then the problem is structured/restructured so that initial design requirements are clear. This first step of the process will help to understand the complex problem. Team building and understanding of the problem (Step 2) then development of collective intelligence (Step 3) phases are accomplished by using Interactive Management (IM). Development of collective intelligence will help to decompose the complex problem (Step 4) into levels through Interpretive Structural Modeling (ISM). Building collective intelligence to understand how factors affecting high speed train system-of-system (SoS) performance and their relationships are an important part of interpretive structural modeling. To have successful IM, professional domain is used iteratively. As shown in Fig. 2, TD team must question and check if the research is useful for societal practice.

The process started by team building and identifying the societal problem as follows.

3.1 Team building and collective understanding of the problem through interactive management (IM)

IM methodology fosters collaboration of group members who share a commitment to solving complex issues within a structure that uses systematic

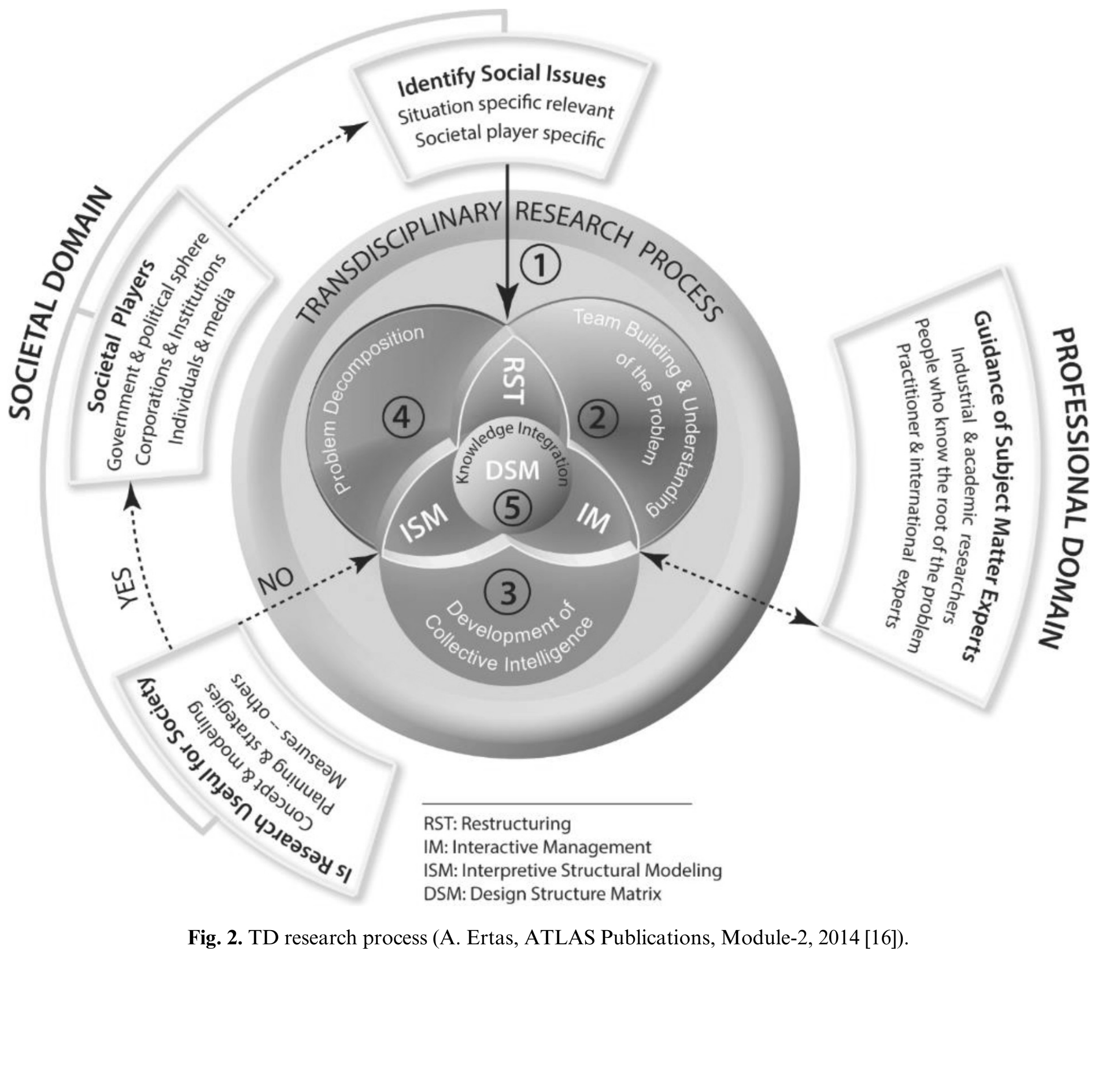

Fig. 2. TD research process (A. Ertas, ATLAS Publications, Module-2, 2014 [16]).

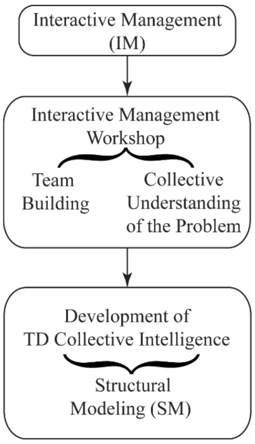

Fig. 3. Management of complexity through IM.

and logical reasoning. Fig. 3 shows the management of complexity through interactive management. As shown in the figure, IM involves two closely linked IM phases—Interactive Management Workshop (IMW) and Development of Collective Intelligence (DCI).

At the beginning of the class, 17 students were broken into 4 preliminary sub-project teams to develop their own independent project concept. Three of the teams consisted of 4 students, and the fourth research team had 5 students. This was due to the makeup of the class. Teams were randomly selected, so members of the team often had no previous working experience with others in their team. Using video-audio conferencing, e-mail, forums and chat as communication platform (Blackboard Collaborate recording), IM workshops were organized where sub-project teams introduced their project proposals (concepts) about the project that they would be exploring. This pilot TD design research class also included the use of video recording of each class meeting as a means of data collection.

Video recording for classroom-based research not only engaged the IM facilitator (Dr. Ertas) and students together in a dialogue but also maximized the accessibility and effectiveness of all workshop communications. Research teams were allowed to generate the following 4 different project concepts:

1. Texas Eco Railways (high speed train system design).
2. Tidal power.
3. Water crisis.
4. Lubbock weather.

Through dialog, each idea was discussed in detail in class meetings. Advantages and disadvantages of each project concept were identified. Each concept was voted and ranked. Finally, two closely ranked project concepts were considered as candidates for online voting by the students. "High Speed Train System Design" was selected as the final project concept. This selected research project was decomposed into 4 main sub-systems to create Expertise Groups. They are:

1. Economic Modelling.
2. Mechanical Design.
3. Electrical Design.
4. Social Issues.

After the final research project concept is created, depending on the students' interest and area of expertise, sub-project teams were reorganized to develop the final proposal for designing a high speed train system. Outcomes obtained with the IM process include [17]:

Learning. Students engaged in an IM activity are exposed to a real sharing of ideas and information, and hence are actively learning about the research project at hand.

Commitment. The final project concept is organic, and created through the collaboration of students and instructors. Through this kind of approach, genuine commitment can be achieved.

Documentation. During the IM process, information and decisions generated by team members were recorded and organized, and provide the basis for broader diffusion of the outcomes.

3.2 Development of TD collective intelligence & complexity decomposition

Interpretive Structural Modeling (ISM)—was used for the development of collective intelligence. Fig. 4 [4] shows the flow chart of the Interpretive Structural Modeling process and the factors effecting the high speed train system design. Interpretive Structural Modeling (ISM), a methodology for dealing with complex issues was proposed by Warfield in 1973. It is a computer-assisted learning process that provides fundamental understanding of how various parameters (elements, variables, system components, etc.) relevant to the problem or issue are interrelated and thus helps researchers to structure them in a meaningful manner to develop collective intelligence to overcome challenging complex problems.

TD Collective Intelligence—Transdisciplinarity provides a good framework and adds to the current approaches for collective intelligence. Transdisciplinary collective intelligence is a new mode of information gathering, knowledge creation, and decision-making that draws on expertise from a wider range of organizations (academic or non-academic) and collaborative partnerships (see Fig. 4). Transdisciplinarity could add two dimen-

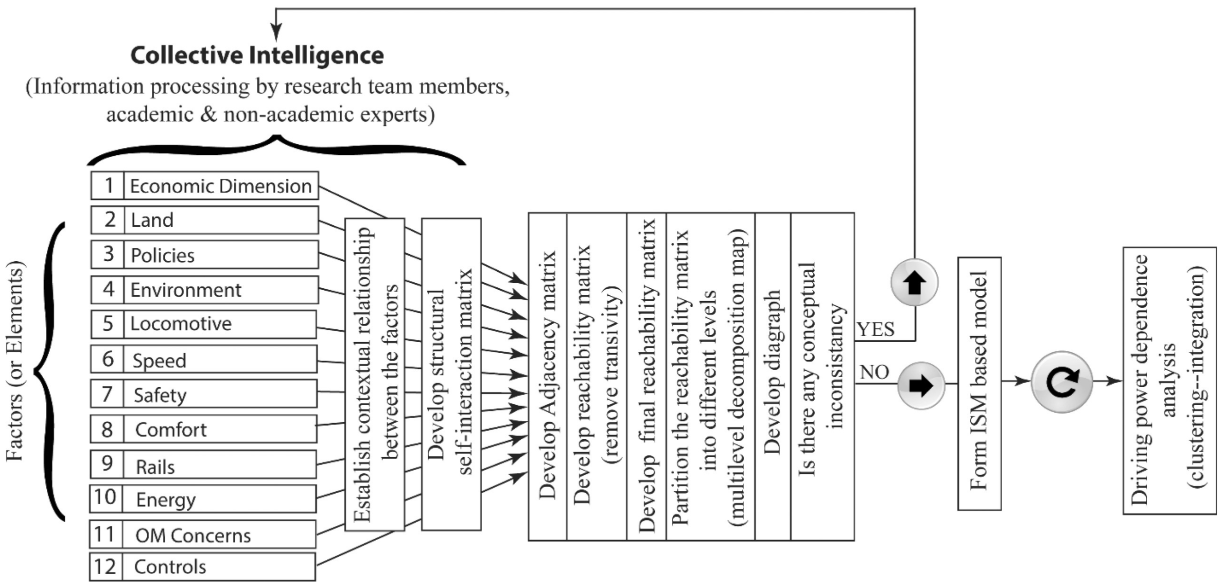

Fig. 4. Management of complexity through IM [16].

sions to knowledge production: first, building collective methods and formulation of practices in addition to knowledge (data, concepts) and second, the identification of common problems collaboratively. Through brainstorming and consultation with the domain experts, student research group members worked together to document all the possible factors (elements) whose relationships are to be modeled. Then the most important factors were identified for the model development. Following the flow chart shown in Fig. 4, relationships among the design factors are developed (see Fig. 5).

As shown in Fig. 5, the complex high speed train system design is decomposed to eight levels and shows how the factors affecting system design are interrelated. For more information about the ISM approach refer to reference [17].

4. Results and discussions

4.1 Discussion on High-Speed Train System-of-systems (SoS) Design

The hypothetical example of a high-speed train System-of-systems (SoS) operating in the Texas Triangle designed by students in this TD senior design class can streamline and benefit travel within the state. The system will reduce carbon output with energy efficient technologies, as well as taking a high number of vehicles off the road. This system will benefit the state as well as the people who live in it.

Factors in designing and developing a high-speed train SoS, shown in Fig. 4, are simplified by lumping similar factors serving the same purpose. Such factors as Electrical Design may include: controls systems, power delivery, amenities, and power sourcing. Mechanical Design issues may include: rail system, train design, maintenance plan, and station design. Social issues may include: safety regulations, environmental concerns, route management, land usage, social impact. Economics may include: marketing, funding, and competitive pricing. Designing and developing an ideal SoS is not an easy task. Many subsystems (e.g., Electrical, Mechanical, Economic, Social, etc.) must be integrated within the TD domain to achieve an overall optimum SoS solution.

One of the objectives of this study was to introduce a new TD research process model in education that deals with such complex system development by creating and using collective intelligence through a collaborative transdisciplinary effort. Interpretive Structural Modeling (ISM), a methodology for dealing with complex SoS design and development is the key component of this research. Building collective intelligence to understand factors affecting SoS performance and their relationships, are an important part of interpretive structural modeling.

Four main important factors—locomotive design, speed, comfort, and rails shown in Fig. 5–are the most integral factors. These need to be analyzed before other factors as most of the other factors depend on them. For a high-speed train system, the main goal must be balancing consumer travel needs with the project's economic need to be profitable. However, in some areas, laws and regulations can also be major barriers to overcome.

As shown in Fig. 5, factors such as energy, controls, and operation maintenance concerns, are positioned at the top of the hierarchy. They are also

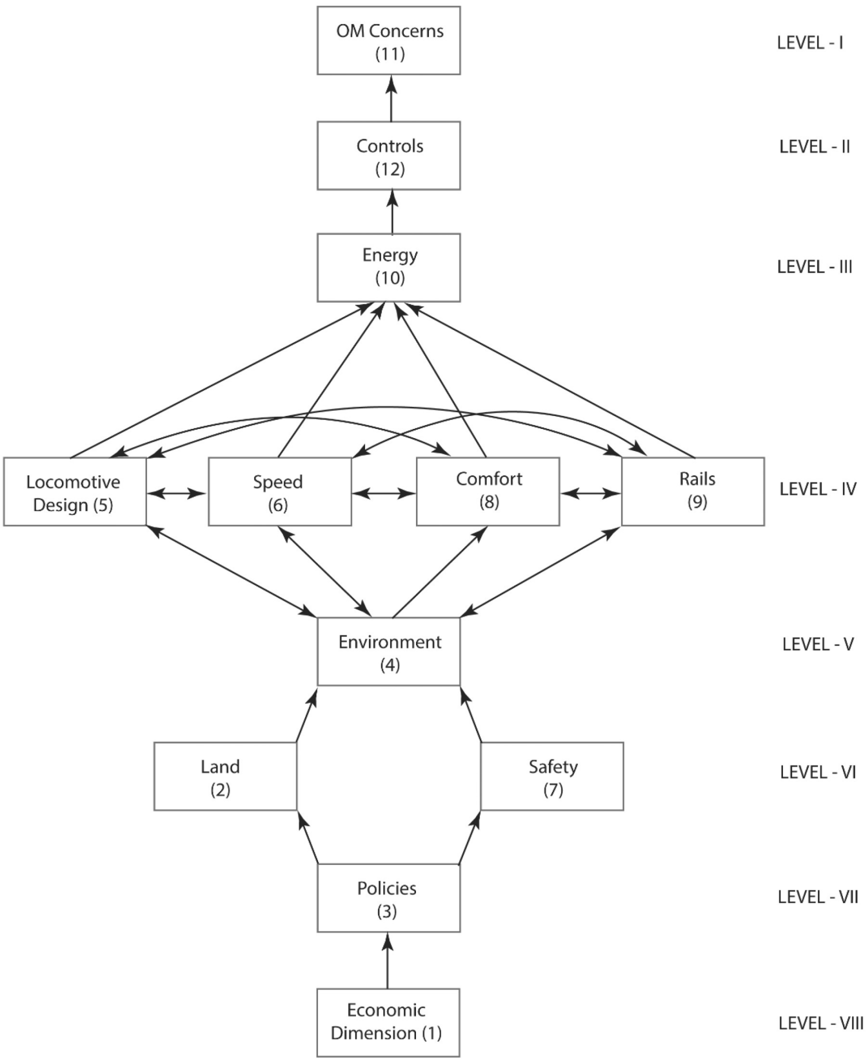

Fig. 5. Relationships among the design factors (Directed graph).

very significant measures for the development of successful high-speed train systems. Of course, one of the main reasons behind creating a high-speed train system is to be more energy efficient as a means of transportation. Controls and the operational concerns are two of the most important factors for having continued success. These three factors are strongly interrelated. These higher-level factors have greater influence on the high speed train system. Hence, when designing and developing such a project, these three factors should be evaluated first, and then kept constant as much as possible during the performance improvement process. In other words, we needed to first make sure that this project would be energy efficient, and then that the control systems would allow for a consistent high speed train network, and then we could work on iterating and evolving the other factors toward success.

As shown in Fig. 6, all performance measures of factors effecting SoS have been classified into four categories. Cluster I include autonomous factors. We can see from the figure they have low driving power and low dependence; therefore, they can be eliminated from the SoS. For this particular case, no factors can be identified as an autonomous factor. This indicates that there is no disconnected factor from the SoS.

Dependent factors with low driving power and high dependence are contained in Cluster II. As seen in Fig. 6, Energy (factor 10), Controls (factor (11) and OM Concerns (factor 12) have a smaller guidance power, but they have high dependency. These factors are affected by other factors of the system-of-systems, but they may not affect other factors.

Cluster III, the linkage factors, is the most delicate of the four clusters. This includes the factors that have high driving power as well as a high dependency. These factors include Environment issues (4), Locomotive design (5), speed (6), comfort

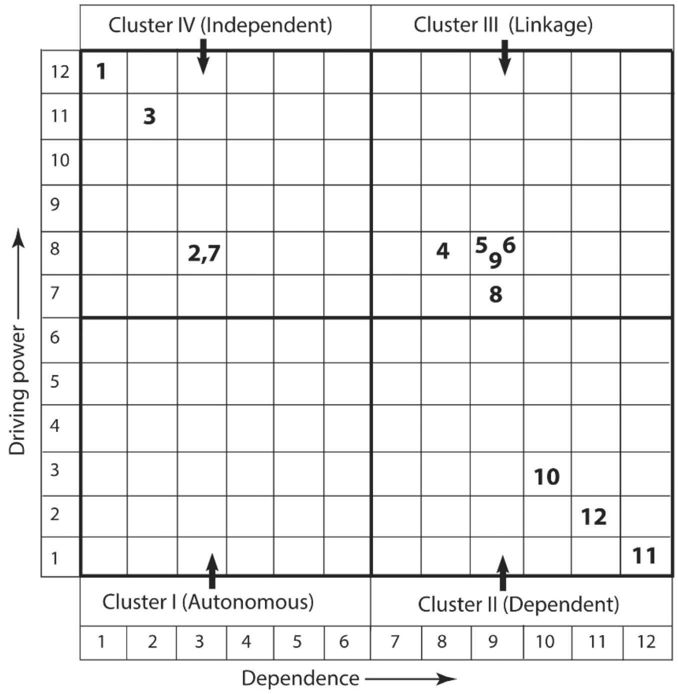

Fig. 6. Performance measures of factors effecting SoS classified into four categories (MICMAC Analysis).

(8), and rails (9). Due to the nature of linkage factors, they not only affect, but also depend on other factors as well. There is inter-relationality. This creates a precocious and complex system that must focus on balancing these five factors in order to incorporate them into the system, without putting the whole project in peril.

The fourth and final Cluster, the independent factors, is comprised of factors that have very high driving factors with minimal dependency. In this cluster, the factors of Economic Dimension (1), Land (2), Policies (3), and Safety (7) can be found, and each of these factors have the potential to make, or break the project and they are influenced largely by external factors. If the project is not economically sound, it will never leave the planning stage. Failure to follow policies set by parties in authority can eliminate the project at any phase. Without having rights on continuous land, there is no route that a train can follow. Lastly, if the safety of the customer is not guaranteed, legal and financial trouble, as well as a loss of credibility, would cause the project to fail. Even though they are critical to the success of the system, their low dependency factor means that once the factors have defined criteria they can be ignored as long as the criteria is met.

4.2 Discussion on Students' TD learning

After obtaining approval from Texas Tech University's Institutional Review Board, two faculty members, one from the College of Education one from the Business School, developed a pre-test and post-test for 36 students (17 students in the experiment section and 19 students in the control section). Pre- and post-tests were given to measure transdisciplinary knowledge gained from taking the TD Design course. The pre-test was a set of questions given to students before the class begins in order to determine their TD knowledge level at the start of the course. After the completion of the TD Design course, students were given a post-test to answer the same set of questions.

Students were unaware of the nature of the TD design study when they registered for the course and students were not allowed to switch sections after they registered. Both the experimental section and the control section included all male students. In the experimental section, there were 70.5% white males, and 29.5% racially diverse males (African-American and Hispanic). In the control section, there were 74% white males, and 26% racially diverse males. As part of this study, we wanted to explore whether or not TD pedagogical methods had a more, less, or similar effect on underrepresented groups as compared to white males. While our sample size was too low to make robust claims about TD effects on underrepresented students, our findings do show some differences. This is explained in more depth below. All the students in both sections were mechanical engineering senior students. An independent sample t-test indicated that upon entering the design course, grade point average of students in both experiment and control groups did not have significant statistical difference in grade point averages at the 95% (two sided) level of confidence in two means of GPA of two sections.

In order to ensure that the survey results were credibly grounded in data, the following three strategies were used:

1. We decided to collect survey responses for pre-test and post-test anonymously, and
2. The survey was conducted by two faculty members from the College of Education and the Business School who were not involved with teaching the TD Design course.
3. The study was approved by Texas Tech University's IRB.

The fall of 2015 semester was used as a pilot semester to test out TD Learning and how the TD knowledge is used to address complex problems. Data from Fall of 2015 semester students were collected and analyzed.

In order to better understand TD pedagogical techniques, and whether the use of TD techniques would lead to an increase in TD skills, students were asked to rate themselves on factors such as: trust, creativity, and other traits associated with TD problem solving. Students were asked in both pre and post-tests to answer following four survey questions.

1. Rate your ability to trust other members of this class.
   Low 1 2 3 4 5 6 7 High
2. Rate your ability to use "outside"' knowledge from experts and apply it to complex engineering problems.
   Low 1 2 3 4 5 6 7 High
3. Rate your ability to collaborate across multiple spheres of knowledge and practices (with people from other disciplines) both within and outside of the field of Engineering.
   Low 1 2 3 4 5 6 7 High
4. Rate your creativity level in solving problems.
   Low 1 2 3 4 5 6 7 High

These students were given the same test at the end of the semester. The following Fig. 7 shows the outcomes of these tests.

Data Analysis

Data collected through this TD design class is modeled by location scale "t" distribution as shown in Fig. 7. This figure shows pre and post-tests results for both experiment and control groups. To address whether TD learning experiences were statistically significant, *Confidence Interval Estimation* based on the difference in Two Means (Variance Unknown) test was used. Since the sample size drawn from the normal population is less than 30, the "t" distribution is used to compute the confidence interval for the difference in two means, $(\mu_1 - \mu_2)$. We assume that variances are same within the two populations. This assumption is often made in comparing two manufacturing processes. This unknown variance, can be estimated by using a "combined" or "pooled" estimator. The equation for pooled estimator is

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$$

In the analysis, a typical 95 percent level of confidence with two-tailed test is used ($p = 0.025$). For

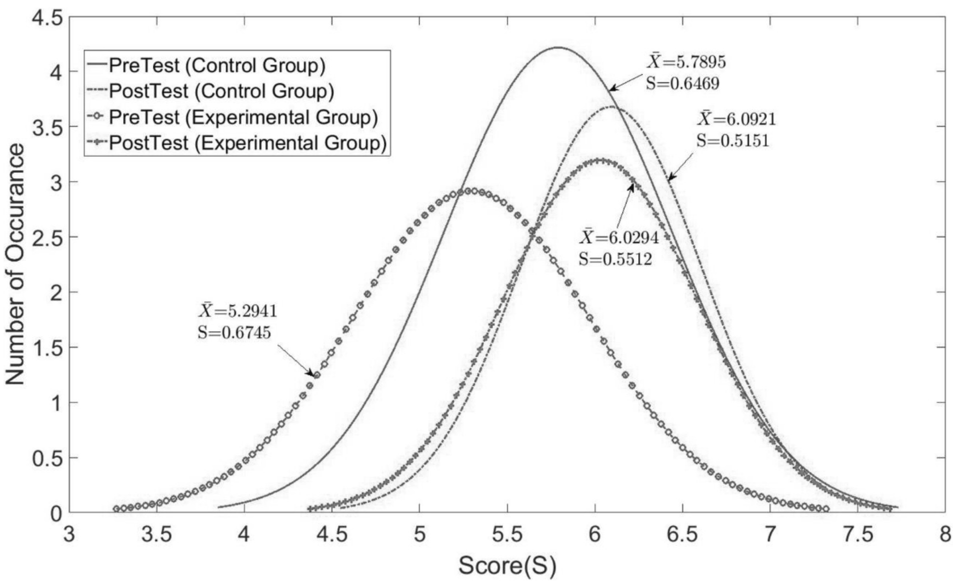

Fig. 7. Measuring TD learning.

testing the difference in two means, we used the following test hypothesis – if the confidence interval includes ($\mu_1 - \mu_2$=0), we will assume that there is no statistical difference in TD learning at a given level of confidence. The two-sided confidence interval for the difference in means, ($\mu_1 - \mu_2$) is given by

$$(\bar{x}_1 - \bar{x}_2) - t_{\alpha/2,n_1+n_2-2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \leq (\mu_1 = \mu_2) \leq$$

$$(\bar{x}_1 - \bar{x}_2) + t_{\alpha/2,n_1+n_2-2} S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

Using above mentioned two equations Table 1 was formed. Table 1 shows that there is a statistical difference for the experiment section (confidence interval does not include ($\mu_1 - \mu_2$) = 0 at the 95% level of confidence in two means. By checking means of both pre and post-test results, we can conclude that students' TD learning in this section is significant whereas the TD learning for the control section is insignificant. However, it is clear from the calculated values of standard deviations for pre and post-tests, that in both sections, students' TD learning approached the mean value.

Seventeen students' individual TD learning in the experiment section is shown in Fig. 8. Although students number 3, 6, 7 and 9 didn't show any improvement in TD learning, the remaining thirteen students' TD learning has increased. It is interesting to note that, number 8 minority student showed significant jump in TD learning compared with the other students.

The connection between race/ethnicity and TD learning is shown in Table 2. The pre and post-test results for 4 survey questions show differences in TD learning between different population groups in the experiment section. The summary of results shown in the table reveals that the ethnic minority students performed 20% better than the white students for question #1 (Q1). Ethnic minority students' ability to trust other members of the class improved as compared to white students. While the standard deviation for the white students remains same, the standard deviation for ethnic minority students was significantly reduced. This indicates that all the ethnic minority students' degree of ability to trust other members of the class is getting close to similar (grouped closely around the mean of SD = 0.45).

The calculated mean values for question #2 also

Table 1. Summary of calculations for control and experiment groups.

Sections	S_p	$v(df)$	$\leq (\mu_1 - \mu_2) \leq$	$\bar{X}_{pre}$	$\bar{X}_{post}$	S_{pre}	S_{post}
Control	0.585	36	$-0.675 \leq (\mu_1 - \mu_2) \leq 0.069$	5.7895	6.0921	0.6469	0.5151
Experiment	0.616	32	$-0.877 \leq (\mu_1 - \mu_2) \leq -0.593$	5.2941	6.0294	0.6745	0.5512

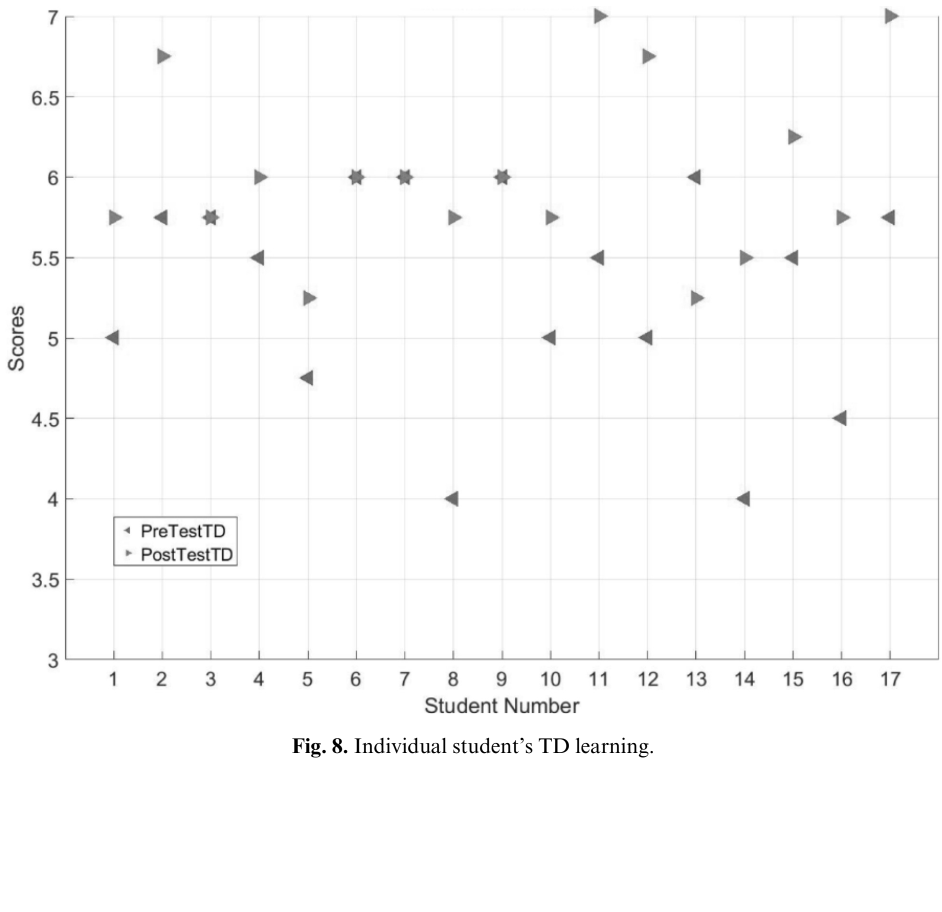

Fig. 8. Individual student's TD learning.

Table 2. Pre and Posttests results by race/ethnicity

Tests	Race/ Ethnicity	Q1		Q2		Q3		Q4		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Pre-Test	White	5.08	1.08	5.67	1.15	5.58	1.00	5.00	0.95	5.33	0.63
	Minority	4.60	1.52	5.20	0.84	5.80	0.84	5.20	0.84	5.20	0.84
Post-Test	White	6.08	1.00	6.17	0.83	6.25	0.62	5.92	0.90	6.10	0.64
	Minority	5.80	0.45	5.80	0.84	5.80	0.45	6.00	0.71	5.85	0.14

indicates the similar improvement for ethnic minority students—their ability to use ''outside''' knowledge from experts to solve complex problems is promising as compared to white students. However, standard deviation for ethnic minority students remains same (SD = 0.84).

This situation reversed for question #3. While ethnic minority students' ability to collaborate with others from different engineering fields remain the same (Mean = 5.80), white students' collaboration ability increased (12%).

For question #4, both white and ethnic minority students' creativity level in solving problems showed similar improvements. Overall, both white and ethnic minority students achieved some level of proficiency in transdisciplinarity. However, change in total standard deviation (from 0.84 to 0.14) indicates that at the end of experiment class the ethnic minority students' level of transdisciplinary understanding became close to each other—in other words, transdisciplinary practice shows demonstrable impact on ethnic minority students learning. Our results, even limited by a small sample size, give credence to the claim that the collaboration, support, and engagement—all integral to TD methods—improves the STEM learning of underrepresented groups.

One of the most interesting points to arise from our study was that that students in the traditional design course (control group) actually experienced a decrease in creativity and collaboration (TD) skills. This suggests that traditionally taught design courses can actually create regression in the types of skills (TD skills) that are needed in the workplace of the 21st Century. Students in the TD-based course experienced an increase in the types of skills (collaboration, complexity, creativity, context-visualization) that are needed in the engineering workplaces of today.

We also examined students' abilities to solve complex problems. Students would have to demonstrate an understanding of the fact that many real-world problems require knowledge and skills from multiple disciplines in order to be solved. The last question on our pre- and post-test tried to get at this concept. The results of this question are examined in the section below.

Table 3 displays a scoring rubric with four score levels that was developed to guide the evaluation of student TD knowledge-gain in the TD Design experiment section (adapted from Montgomery, [18]). As Table 3 illustrates, each score category describes the characteristics of a response that would receive the respective score. In developing a scoring rubric, we have identified clearly the qualities that need to be displayed in a student's research work to demonstrate skillful performance [19].

In this study, through pre and post-tests, students in the experiment section were given the following research problem. We asked them to answer the

Table 3. Rubric for the research problem (adapted from Montgomery [18])

Skill	4 Points	3 Points	2 Points	1 Points
Understanding the problem	Shows complete understanding of the problem and has insights beyond the problem.	Shows complete understanding of the problem.	Shows partial understanding of the problem; needs teacher assistance to clarify.	Requires teacher assistance to understand the problem.
Making a plan	Develops sophisticated strategies and applies them within an effective plan.	Independently chooses and applies appropriate strategies and applies them effectively.	Shows evidence of plans and use of a strategy, which may or may not be applied effectively.	Needs assistance to choose an appropriate strategy; applies a strategy such as ''guess and check'' in a random way.
Propose a Solution	Provides a correct and complete solution; may show more than one way to solve the problem.	Independently provides a correct and complete solution.	Makes a minor error in taught process leading to a wrong answer or incomplete solution.	Gives incorrect solution even with direction.

question to the best of their ability by providing as much detail as possible.

> "Golden Eagles and Prairie Chickens have had declining populations over the last several decades as a result of habitat loss due, in part, to the installments of wind turbines, and wind energy farms. Yet, we also know that wind turbines are a valuable source of clean energy. What skills, tools, and knowledge would you need to create an effective and efficient wind farm while also protecting the natural habitat of animals like the Prairie Chicken and Golden Eagle?"

Students' responses for pre and post-tests were evaluated by three people and the average of their grading is plotted in Fig. 9. Calculated pooled estimator, S_p was 0.893 and the two-sided confidence interval for the difference in means, $(\mu_1 - \mu_2)$ was: $-1.012 \leq (\mu_1 - \mu_2) \leq 1.189$.

Since the above interval does include $(\mu_1 - \mu_2) = 0$ there is no significant difference between the results of pre and post-tests. This conclusion was expected. Students in the experiment section during the fall semester of 2015 learned and practiced how to build a team and how to identify complex problems. They also learned TD skills and tools to decompose complex problems to meaningful and understandable simple levels. Although they had a complete understanding of TD research process, they did not practice TD research. The research problem that we have asked the students on Golden Eagles and Prairie Chickens was a complex social research problem that would require the types of skills needed in the 21st Century workplace, and thus, represents a prime example of a TD research question

Figure 9 shows slight shift in means between pre and post-test results but no significant change in standard deviation was observed.

Multiple studies in the field of education have shown that creating collaboration and spaces for students to work with and be challenged by each other can create real learning gains—deeper understanding and better retention of concepts. Aukrust [20] has argued that the act of learning is nurtured when we engage with each other and with our surroundings. Brophy [21] further argues that cognitive development and learning happen best, and the development and the activation of new schema happen most efficiently, when students interact with each other in ways that allow them to hear multiple perspectives. Gambrell et al. [22] also validate the idea that learning happens best when students are involved in a community where they talk to each other and hear multiple points of view and experiences. Current research on cognition underscores not only the need for students to talk to each other, and to feel comfortable and supported by each other, but also for students to develop their own thinking by *hearing difference*; that is, by seeing

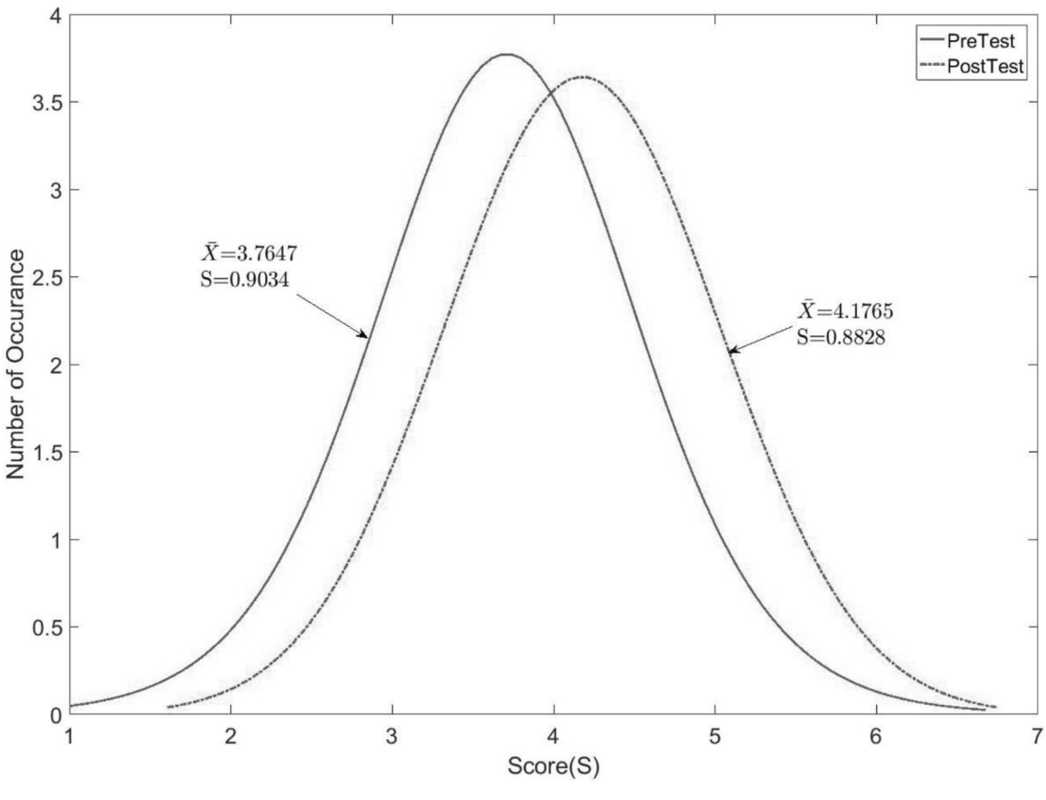

Fig. 9. Results of Golden Eagles and Prairie Chickens research problem.

things from multiple perspectives. An environment that facilitates learning from each other, talking with each other, and hearing multiple—and diverging—experiences and ideas leads to more engaged and motivated students; to better learners and deeper learning. This is exactly the type of environment that is promoted by TD-based pedagogy. And, in our study, we have seen that TD methods truly can lead to increased collaboration, sharing of differences, and trust. We have seen that this type of teaching can lead to better learning.

Educational research as shown that pedagogical strategies which promote collaboration are particularly beneficial to underrepresented students. Pedagogical methods that consciously create opportunities for collaboration, for learning from each other, for working in small groups, and for multiple types of learning, have been shown to increase engagement and the retention of underrepresented groups. Students who may not otherwise feel comfortable interacting in a standard lecture-based class tend to have the most gains when instructors employ methods that focus on interaction and the bringing together of multiple types of knowledge and interaction. Nelson [25] states that particularly in STEM courses, it is important to create spaces for students to be creative, collaborate, and find their own voice, and contends that most traditionally-taught STEM courses are unintentionally biased against minority students, and that in order to encourage diverse perspectives (and a diverse student body) it is necessary to come up with more collaborative and creative methods of engaging in STEM learning. Because TD methods aim to encourage multiple types of collaboration, nurture multiple perspectives, create safe environments for diversity, and develop communities of learners that span students, academics, and professionals working in the field, TD is ideal for creating the type of environment that is nurturing to underrepresented people in STEM. TD methods can promote the kind of diversity, dynamism, experience, and creativity needed in the field, and by society more broadly. This study validates this claim: that TD-methods support the learning of underrepresented groups.

5. Conclusion

The Transdisciplinary Design Studio (TD^{2}S) for Collaborative Research and Education (CORE) was integrated with the new TD course. TD class provided our students with the prospect to create, collaborate, communicate, and to enhance learning and knowledge sharing for problem solving. In the TD class, students learned skills and techniques needed to be highly creative when they take a job after graduation. The results of this paper showed that students in the experiment section during the fall semester of 2015 learned and practiced how to build a team and how to identify complex problems.

TD methods of pedagogy and research, aim to create: more creative problem-solving skills in engineering students, more innovative engineering designs, better understanding of how to tackle real-world complex problems, better collaboration, and increased engagement for underrepresented groups. Few studies have been done on how, and if, TD methods fulfill that promise. This study works to fill that gap. While our results are preliminary and our overall sample size is small, we have nevertheless showed some real gains in skills and knowledge for students who took the TD-based course. Namely, this study validated that TD-methods support the learning of underrepresented groups—transdisciplinary practice showed demonstrable impact on ethnic minority students learning.

This paper highlights our work with engineering courses that included males only. As part of our future research endeavors we also hope to test TD pedagogy and TD research skills in classes that include males and females. We are intrigued by our findings thus far that TD methods increase the learning for some underrepresented groups. In addition, we believe that the findings identified also show that TD-based courses can engage students in highly complex research questions and foster the attainment of critical collaborative and creative skills. This study also foregrounds the question of whether traditional design courses are actually causing regression of collaboration, complexity, and creativity in the students. We look forward to testing these methods in more classes. More work needs to be done on the ways that TD-research methods can lead to better innovation, more creative problem-solving, and greater gains for and retention of underrepresented students. The continuation of our current research project on TD methods in the classroom aims to do that research.

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